NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3950

CHARTS FOR THE ANALYSIS OF FLOW IN A WHIRLING DUCT

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Washington
May 1957

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SUMMARY

Charts are developed for the analysis of flow in a whirling constant-diameter duct. These charts permit the determination of the duct-exit Mach number, or the Mach number at any point along the duct, for practical ranges of duct-inlet Mach number, duct-tip Mach number, friction factor, ratio of ambient temperature to duct-flow total temperature, ratio of duct-tip radius to duct hydraulic diameter, and heat conductivity through the duct wall and surrounding material. The method of using the charts is illustrated through the computation of a sample problem.

INTRODUCTION

In certain types of rotor tip-mounted propulsive systems being used in helicopters, for example, the pressure-jet system, the air supply is ducted through the rotor blade. In order to obtain a complete analysis of such a system, a knowledge of the flow properties in the duct is required. The usual method of analysis requires a time-consuming numerical integration of a nonlinear differential equation similar to those derived in references 1 and 2. The purpose of this paper is to perform this integration and to present the results in chart form for a range of parameters which include the duct-inlet Mach number, the duct-tip Mach number, the duct-inlet temperature, the heat-transfer rate, the friction factor, and the ratio of the duct hydraulic diameter to the duct-tip radius. The charts are presented for a constant-diameter duct; however, possible applications of these charts for ducts of varying diameter are discussed.

The analysis presented herein is limited to steady-state, one-dimensional, compressible, viscous flow and applies only to straight ducting.

SYMBOLS

A	duct cross-sectional area, sq ft
a	speed of sound, fps

c_p specific heat at constant pressure, ft-lb/slug-$^{\circ}$R

D duct hydraulic diameter, $\frac{4A}{\text{Perimeter}}$, ft

h local heat-transfer coefficient based on difference between wall temperature and adiabatic wall temperature, ft-lb/ft^2-sec-$^{\circ}$R

K_f friction factor, $\tau\Big/\frac{1}{2}\rho u^2$

k thermal conductivity, ft-lb/ft-sec-$^{\circ}$R

M duct Mach number

M_T duct-tip Mach number, $\Omega r_e\big/a_a$

Q heat added to fluid element per unit mass per unit surface area, ft-lb/ft^2-slug

q heat transferred from fluid element per second, $\frac{\text{ft-lb}}{\text{sec}}$

R thermal resistance between duct wall and outer wall of blade per running foot of blade, sec-$^{\circ}$R/ft-lb

r radial distance from center of rotation to fluid element, ft

r_e radial distance from center of rotation to exit of duct being considered, ft

S surface area through which heat is transferred per running foot, sq ft

T static temperature, $^{\circ}$R

T_t total temperature, $^{\circ}$R

u duct-flow velocity, fps

x ratio of fluid-element radius to duct-tip radius, r/r_e

γ ratio of specific heats

κ ratio of duct heat-transfer coefficient to overall heat-transfer coefficient (defined in eq. (5b))

ρ mass density, slugs/cu ft

τ friction shearing stress, lb/sq ft

ϕ Mach number function defined in equation (8b)

Ω rotor angular velocity, radians/sec

Subscripts:

a ambient air

aw adiabatic wall

e duct-exit station

i duct-inlet station

o center line of rotation station

ow outer wall, that is, wall exposed to ambient air

w duct wall

ANALYSIS

In order to develop an expression for the steady, one-dimensional, compressible, viscous flow in a whirling duct, it is necessary to analyze all the forces and energies acting on a fluid element. An analysis of this type using the momentum and continuity equations yields a relation, as given in reference 1, between the duct Mach number and the independent flow variables. This relation may be written in the form

$$\frac{dM^2}{dx} = -\frac{2M^2\left(1 + \frac{\gamma - 1}{2} M^2\right)}{1 - M^2} \frac{dA/A}{dx} + \frac{4\gamma M^4\left(1 + \frac{\gamma - 1}{2} M^2\right)}{1 - M^2} \frac{K_f r_e}{D} -$$

$$\frac{2M^2\left(1 + \frac{\gamma - 1}{2} M^2\right)^2}{1 - M^2} \gamma M_T^2 \frac{T_a}{T_t} x + \frac{M^2\left(1 + \gamma M^2\right)\left(1 + \frac{\gamma - 1}{2} M^2\right)}{1 - M^2} \frac{dT_t/T_t}{dx} \tag{1}$$

which gives the effect of duct area, friction, whirling, and temperature on the duct Mach number. A solution to equation (1) is possible for known values of the independent variables. However, the total-temperature variation along the duct is dependent upon M_T and $K_f r_e/D$, and it is, therefore, necessary to analyze the energies involved in the flow system.

The Energy Equation

For a steady-flow process, the energy equation is a balance of all the energies involved in a system. Therefore, for a fluid element in a duct subjected to a centrifugal force in the flow direction, the energy equation for constant specific heat is

$$c_p \frac{dT_t}{dr} - \Omega^2 r - Q \frac{4A}{D} = 0 \tag{2}$$

The heat transferred from the duct may be expressed as

$$Q \frac{4A}{D} = \frac{4}{D} \frac{h}{\rho u}\left(T_w - T_{aw}\right)$$

The adiabatic wall temperature T_{aw} is assumed to be equal to the total temperature; that is, the recovery factor is assumed to be equal to one. The error involved in such an assumption is very small at low duct Mach numbers.

Substituting the preceding expression for the third term of equation (2), nondimensionalizing, and using the relation $a_a^2 = (\gamma - 1)c_pT_a$ reduces equation (2) to

$$\frac{dT_t/T_t}{dx} = (\gamma - 1)\frac{T_a}{T_t} M_T^2 x + \frac{4h}{c_p \rho u} \frac{r_e}{D}\left(\frac{T_w}{T_t} - 1\right) \tag{3}$$

Equation (3) may be further simplified by use of Reynolds analogy which states that

$$\frac{h}{c_p \rho u} = \frac{K_f}{2}$$

This relation is fairly accurate at subsonic Mach numbers (refs. 3 and 4). Equation (3) may then be expressed as

$$\frac{dT_t/T_{t,i}}{dx} = (\gamma - 1)\frac{T_a}{T_{t,i}} M_T^2 x + 2 \frac{T_t}{T_{t,i}} \frac{K_f r_e}{D}\left(\frac{T_w}{T_t} - 1\right) \tag{4a}$$

For adiabatic flow in the duct $T_w = T_t$, the total temperature is given by

$$\frac{T_t}{T_{t,i}} = 1 + \frac{\gamma - 1}{2} \frac{T_a}{T_{t,i}} M_T^2\left(x^2 - x_i^2\right) \tag{4b}$$

If the flow is not adiabatic, the ratio of wall temperature to total temperature must be determined as a function of x.

Ratio of wall temperature to total temperature.- An analysis of the heat transfer from the duct to the ambient air results in a relation between the temperatures of the duct flow, the duct wall, and the ambient air. This relation may be expressed as

$$\frac{T_w}{T_t} = 1 - \kappa\left(1 - \frac{T_a}{T_t}\right) \tag{5a}$$

where κ is the ratio of the duct heat-transfer coefficient (gas to duct wall) to the overall heat-transfer coefficient (from the gas to the ambient air) and is given by

$$\frac{1}{\kappa} = 1 + \frac{hS_w}{h_a S_{ow}} + hS_w R \tag{5b}$$

Equation (5a) assumes the aerodynamic heating of the external skin of the rotor to be negligible.

The ratio of the duct heat-transfer coefficient to the overall heat-transfer coefficient is determined by the heat-transfer coefficient of the gas in the duct, the heat-transfer coefficient between the ambient air and external skin of the rotor, and the internal construction of the rotor blade. It varies from zero for adiabatic flow to about 0.5 for thin-walled ducts in the leading edge of a rotor blade.

The main difficulty in determining a value of κ for a duct in a helicopter rotor blade would be in estimating the thermal resistance between the inner surface of the duct and the outer surface of the rotor blade. However, the effect of heat transfer on the change in Mach number in the duct is small compared with the effect of whirling and friction. It is possible, therefore, to use an approximate value of the thermal resistance to compute κ and the effects of heat transfer on the Mach number variation in the duct.

Total-temperature variation in duct.- The variation of total temperature in the duct may be obtained by substitution of equation (5a) into equation (4a) which gives

$$\frac{d\left(T_t/T_{t,i}\right)}{dx} = (\gamma - 1)\frac{T_a}{T_{t,i}} M_T^2 x - 2\kappa \frac{K_f r_e}{D}\left(\frac{T_t}{T_{t,i}} - \frac{T_a}{T_{t,i}}\right) \tag{6}$$

For a constant-diameter duct, the solution to equation (6) is of the form

$$\frac{T_t}{T_{t,i}} = e^{-2\bar{\kappa}\frac{K_f r_e}{D}(x-x_i)} + \frac{(\gamma - 1)\frac{T_a}{T_{t,i}} M_T^2}{2\bar{\kappa}\left(\frac{K_f r_e}{D}\right)^2}\left\{e^{-2\bar{\kappa}\frac{K_f r_e}{D}(x-x_i)} - 1 + 2\bar{\kappa}\frac{K_f r_e}{D}\left[x - x_i e^{-2\bar{\kappa}\frac{K_f r_e}{D}(x-x_i)}\right]\right\} + \frac{T_a}{T_{t,i}}\left[1 - e^{-2\bar{\kappa}\frac{K_f r_e}{D}(x-x_i)}\right] \tag{7a}$$

where $\bar{\kappa}$ is a mean value of κ for the duct. The term $K_f r_e/D$ is constant for a constant-diameter duct except for the small effect of the temperature variation along the duct on K_f.

Equation (7a) may be simplified for low rates of heat transfer by expanding the exponential terms and keeping only the first two terms of the expansion. The resulting equation is

$$\frac{T_t}{T_{t,i}} = 1 + \frac{\gamma - 1}{2}\frac{T_a}{T_{t,i}} M_T^2\left(x^2 - x_i^2\right) + 2\frac{K_f r_e}{D}\left(\frac{T_a}{T_{t,i}} - 1\right)\left(x - x_i\right) \tag{7b}$$

For values of $\frac{\bar{\kappa} K_f r_e}{D} = 0.007$, the value of $\left(\frac{T_t}{T_{t,i}} - 1\right)$ computed by equation (7b) is within 4 percent of the value computed by equation (7a). The absolute value of $T_t/T_{t,i}$ is well within 1 percent of the value computed by equation (7a).

With the knowledge of the total-temperature variation along the duct as given by equations (6) and (7a), it is now possible to write a general equation describing the flow in a whirling duct.

The General Flow Equation

The general equation describing the flow in a whirling constant-diameter duct may be obtained by substituting equation (6) into equation (1) and simplifying. Thus,

$$\frac{dM^2}{dx} = \frac{M^2\left(1 + \frac{\gamma - 1}{2} M^2\right)}{1 - M^2}\left[4\gamma M^2 \frac{K_f r_e}{D} - (\gamma + 1)M_T^2 \frac{T_a}{T_{t,i}} \frac{T_{t,i}}{T_t} x - 2(1 + \gamma M^2)\frac{\bar{\kappa} K_f r_e}{D}\left(1 - \frac{T_a}{T_{t,i}} \frac{T_{t,i}}{T_t}\right)\right] \tag{8a}$$

Equation (8a) is subject to the same assumptions as equations (1) and (6): namely, constant specific heat and molecular weight, the validity of the Reynolds analogy, and the equality of the adiabatic wall temperature and duct total temperature.

The Mach number at any point in the duct or at the duct exit is dependent upon five parameters: M_i, M_T, $K_f r_e/D$, $T_a/T_{t,i}$, and $\bar{\kappa}$. Accordingly, any attempt to present in chart form the results of integrating equation (8a) would involve a large number of calculations and plots.

A change of variable, however, permits results to be obtained in terms of only four parameters with satisfactory accuracy. Equation (8a) is first rewritten as follows:

$$\frac{1}{K_f r_e/D} \frac{(1 - M^2)dM^2}{M^2\left(1 + \frac{\gamma - 1}{2} M^2\right)} = \frac{d\phi}{K_f r_e/D}$$

$$= \left[4\gamma M^2 - (\gamma + 1)\frac{M_T^2}{K_f r_e/D} \frac{T_a}{T_{t,i}} \frac{T_{t,i}}{T_t} x - 2(1 + \gamma M^2)\bar{\kappa}\left(1 - \frac{T_a}{T_{t,i}} \frac{T_{t,i}}{T_t}\right)\right]dx \tag{8b}$$

where

$$\phi = \log_e \frac{M^2}{\left(1 + \frac{\gamma - 1}{2} M^2\right)^{(\gamma+1)/(\gamma-1)}}$$

$\frac{\phi}{K_f r_e/D}$ is the new variable, and $\frac{M_T^2}{K_f r_e/D}$ is a new parameter. A plot of ϕ as a function of Mach number is given in figure 1 for $\gamma = 1.40$.

The left side of equation (8b) is an exact differential so that its integral is not dependent upon the precise variation of M^2 along the duct. On the right side, the second (centrifugal) term is normally of the order of 5 to 10 times as much as the first or third terms (friction and heat transfer, respectively). Furthermore, the first and third terms have opposite signs and, therefore, tend to cancel. Accordingly, the variation of M^2 along the duct (which affects only the first and third terms on the right side) does not greatly affect $\frac{d\phi}{K_f r_e/D}$ which, in this case, is nearly proportional to $\frac{M_T^2}{K_f r_e/D}$.

The preceding paragraph dealt with large values of $\frac{M_T^2}{K_f r_e/D}$. It is of interest to consider the opposite extreme - that of zero rotational speed. In this case the second term disappears and only the first and third terms remain. At reasonable values of $K_f r_e/D$, there is little variation of M^2 along the duct for this case of zero rotational speed so that the integral of $\frac{d\phi}{K_f r_e/D}$ between the duct inlet and the position being considered is relatively small.

The essential conclusion from the preceding discussion is that it should be possible to choose some typical values of $K_f r_e/D$, to integrate equation (8b) numerically to get $\frac{\phi_o - \phi_e}{K_f r_e/D}$ as a function of the four parameters M_i, $\frac{M_T^2}{K_f r_e/D}$, $\frac{T_a}{T_{t,i}}$, and $\bar{K}$, and to obtain results that are within practical accuracy for any other value of $K_f r_e/D$ within reason. Of course, for large values of $K_f r_e/D$ and high duct Mach numbers, this reasoning is invalid.

Calculation of Whirling Effect at Low

Duct Mach Numbers

As may be seen from figure 1, ϕ varies rapidly with Mach number at low duct Mach numbers. A small error in the calculation of the duct-inlet and duct-exit Mach numbers can cause a significant error in the difference between ϕ_o and ϕ_e. Therefore, the charts presented in this paper are not extended below a duct Mach number of 0.15. For duct Mach numbers below this value, it is suggested that the effects of friction and whirling be computed separately and added. The Mach number variation may then be written

$$M_e^2 - M_i^2 = \left(M_e^2 - M_i^2\right)_{M_T=0} + \left(M_e^2 - M_i^2\right)_{M_T} \qquad (9)$$

The first term on the right side of equation (9) represents the change in Mach number of a nonwhirling duct. This value may be computed from equation (8b) with $M_T = 0$ or by the method given in reference 5. The second term on the right side represents the change in Mach number due to whirling and may be computed by integrating the rotation term of equation (8b). That is,

$$\left(\phi_i - \phi_e\right)_{M_T} = (\gamma + 1)M_T^2 \frac{T_a}{T_{t,i}} \int_{x_i}^{1} \frac{T_{t,i}}{T_t} x \, dx \qquad (10)$$

Since the effect of $\bar{\kappa}$ is very small at the low Mach numbers, equation (4b) may be used to express $T_{t,i}/T_t$. Equation (10) then becomes

$$\left(\phi_i - \phi_e\right)_{M_T} = \frac{\gamma + 1}{\gamma - 1} \log_e \left[1 + \frac{\gamma - 1}{2} \frac{T_a}{T_{t,i}} M_T^2\left(1 - x_i^2\right)\right] \qquad (11)$$

The decrease in Mach number due to whirling may be computed by use of equation (11) and figure 1.

Calculations of the duct-exit Mach number by this procedure show good agreement with data obtained by integration of equation (8b) and with experimental data.

CHARTS FOR ANALYZING THE FLOW IN A WHIRLING DUCT

The charts for analyzing the flow in a whirling constant-diameter duct are presented in figures 2 and 3. The curves were computed by numerically integrating equation (8b) from $x_1 = 0$ to $x = 1.0$ for $K_f r_e/D = 0.06$. Check points for values of $K_f r_e/D$ other than 0.06 were also calculated. The values of $\frac{\phi_o - \phi_e}{K_f r_e/D}$ were determined for the various values of $\bar{\kappa}$, $\frac{T_a}{T_{t,o}}$, M_o, and $\frac{{M_T}^2}{K_f r_e/D}$ assumed.

In figure 2, the positive values of $\frac{\phi_o - \phi_e}{K_f r_e/D}$ as a function of M_o are plotted for a range of values of $\frac{T_a}{T_{t,o}}$ from 0.95 to 0.55, $\bar{\kappa}$ from 0 to 0.5, and $\frac{{M_T}^2}{K_f r_e/D}$ from 0.67 to 16.67. In figure 3, the negative values of $\frac{\phi_o - \phi_e}{K_f r_e/D}$ as a function of M_e are plotted for a similar range of variables. This method of plotting has been used to avoid the difficulty of attempting to plot an $M_e = 1$ curve on a figure having M_o as an abscissa. In such a plot, the $M_e = 1$ curve would be a function of $K_f r_e/D$. As plotted in figure 3, the $M_e = 1$ curve is independent of $K_f r_e/D$.

In order to use figure 3 with only M_o known, it is necessary to find, by trial, the value of M_e that agrees with the known value of M_o. A linear interpolation between given values of $\frac{{M_T}^2}{K_f r_e/D}$ is of sufficient accuracy in the use of the charts.

Effect of $K_f r_e/D$

As mentioned previously, the curves of figures 2 and 3 have been computed for $K_f r_e/D = 0.06$. As a check on the effect of $K_f r_e/D$, calculations have been made for values of $K_f r_e/D$ of 0.02, 0.10, 0.24, and 0.3. These check points are shown in figures 2 and 3. At $K_f r_e/D = 0.10$, the difference in exit Mach number between a calculated curve and the check point at the same $\frac{M_T^2}{K_f r_e/D}$ never exceeded 0.01 for any of the check points calculated. This discrepancy is well within the accuracy of the calculations. It appears, therefore, as though the charts of figures 2 and 3 are substantially independent of $K_f r_e/D$. As further evidence of this independence, calculations at $\frac{T_a}{T_{t,o}} = 0.65$, $M_o = 0.24$, $\bar{\kappa} = 0.3$, $\frac{M_T^2}{K_f r_e/D} = 2.9$, and $K_f r_e/D = 0.5$ give a value of $\frac{\phi_o - \phi_e}{K_f r_e/D} = 2.62$ which agrees with the value obtained from figure 2(d) by interpolation.

Effect of Duct-Diameter Variation

The charts may be used to compute the Mach number variation of a flow passage composed of a number of ducts having different diameters. In this case, the value of r_e is the distance from the center of rotation to the exit of the duct being considered and M_o is based on the diameter of this duct. An application of the charts to this type of duct is given in the sample calculation.

The preceding method can be applied to a tapering duct. However, if the duct tapers rapidly, the increments of duct length that must be used may approach the increments that would be used in integrating equation (8b). In this case, there may be little or no saving in calculation time between the two methods.

Sample Calculation

The application of the charts may best be illustrated by a sample calculation. Assume a duct consisting of two lengths of constant-diameter ducting. The first length extends from the 15-percent to the 70-percent spanwise station and has a value of $K_f r_e/D = 0.10$. The second length extends from the 70-percent to the 100-percent spanwise station and has a value of $K_f r_e/D = 0.12$. Assume that the ratio of the duct area of the second length to that of the first is 0.81. The duct-tip Mach number is assumed to be 0.9 and the duct flow is assumed to be adiabatic ($\bar{\kappa} = 0$). Finally, assume that, at $x = 0.15$, the duct Mach number is 0.40 and the ratio of ambient temperature to total temperature is 0.65.

Then, from equation (4b), $\frac{T_{t,o}}{T_{t,i}} = 0.997$ or $\frac{T_a}{T_{t,o}} \approx 0.65$. At $x = 0.15$,

$$\left(\frac{M_T^2}{K_f r_e/D}\right)_{0.15} = \frac{\left[(0.15)(0.9)\right]^2(0.7)}{(0.10)(0.15)} = 0.850$$

In order to calculate M_o for the first length of duct, assume that $M_e = M_i = 0.40$. Then, from figures 2(d) and 3(d),

$$\frac{\phi_o - \phi_e}{K_f r_e/D} = -0.25$$

and, by use of figure 1,

$$M_o = 0.395$$

For the first length of duct, the Mach number at $x = 0.70$ may be determined from figure 2(d) at

$$\left(\frac{M_T^2}{K_f r_e/D}\right)_{0.70} = \frac{\left[(0.7)(0.9)\right]^2}{0.10} = 3.97$$

Then,

$$\frac{\phi_o - \phi_e}{K_f r_e/D} = 2.45$$

and

$$M_e = 0.345$$

In the second length at $x = 0.70$, the Mach number is 0.455 if a 2-percent total-pressure loss is assumed at the contraction. In order to calculate M_o for the second duct, assume that the Mach number at the inlet to the second duct is an exit Mach number; that is, $M_e = M_i = 0.455$. Thus,

$$\left(\frac{M_T^2}{K_f r_e/D}\right)_{0.70} = \frac{[(0.7)(0.9)]^2}{(0.12)(0.7)} = 4.73$$

and

$$\frac{T_a}{T_{t,o}} = 0.65$$

Using figure 2(d) and assuming values of M_o until the correct value of M_e is obtained yields $M_o = 0.51$.

Then, at $x = 1.0$,

$$\left(\frac{M_T^2}{K_f r_e/D}\right)_i = \frac{0.81}{0.12} = 6.75$$

From figure 2(d),

$$\frac{\phi_o - \phi_e}{K_f r_e/D} = 3.87$$

and

$$M_e = 0.38$$

Since the mass flow and total temperature at the duct exit are known, any other flow property may be obtained.

CONCLUDING REMARKS

Charts have been developed for the analysis of flow in a whirling constant-diameter duct. These charts were presented for a range of variables which include the duct-inlet Mach number, duct-tip Mach number, friction factor, ratio of ambient temperature to duct-flow total temperature, ratio of duct-tip radius to duct hydraulic diameter, and a dimensionless heat-transfer term. The method of using the charts is illustrated through the computation of a sample problem.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., January 3, 1957.

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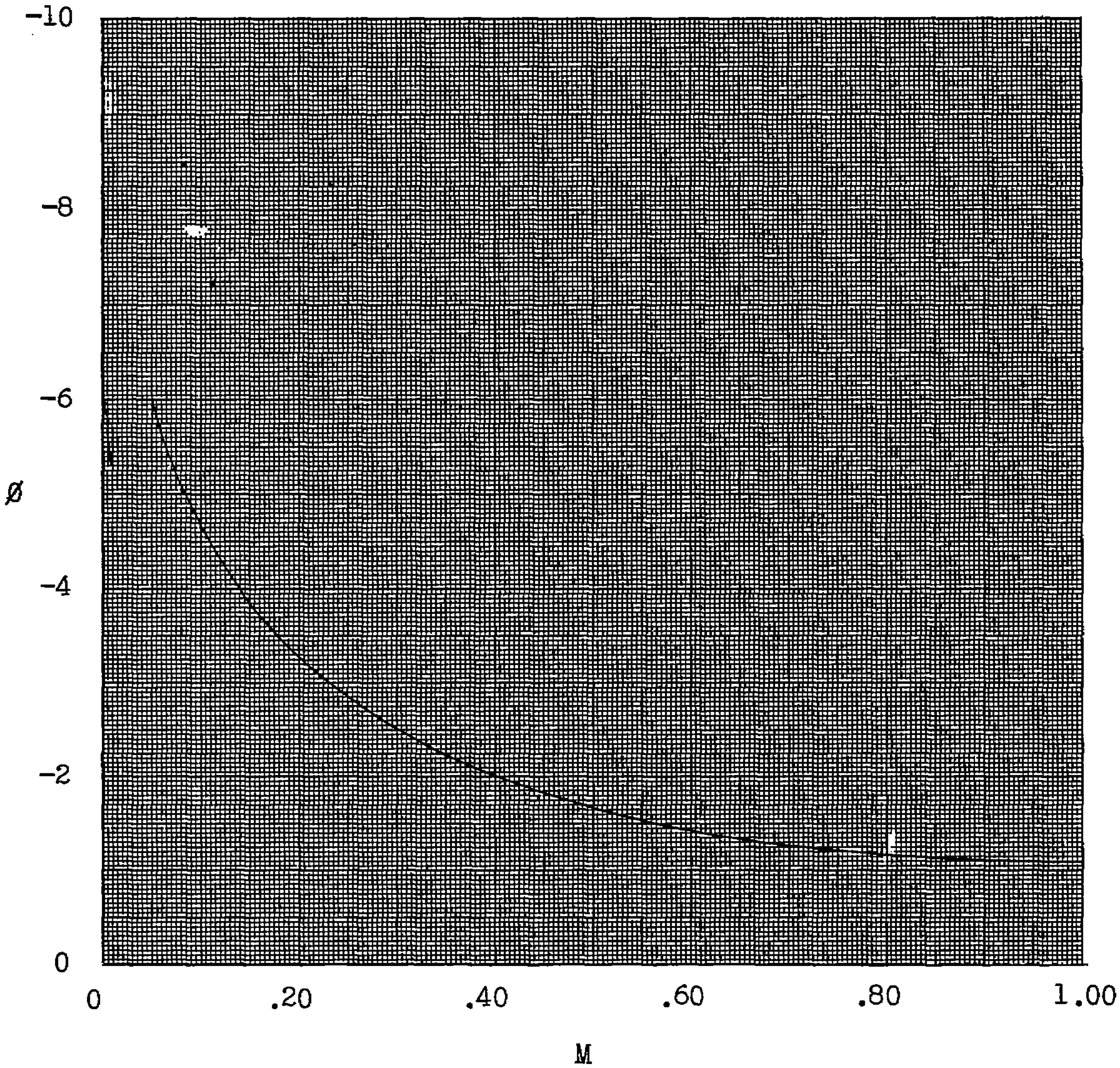
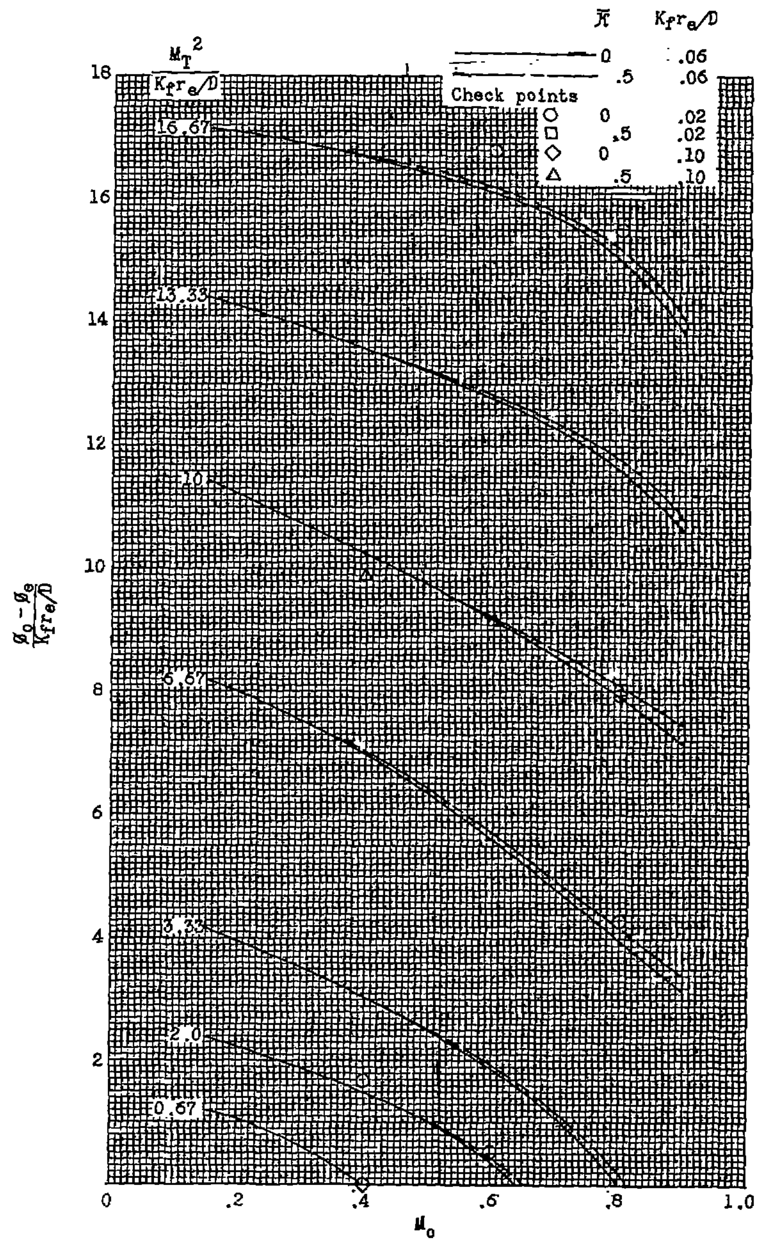


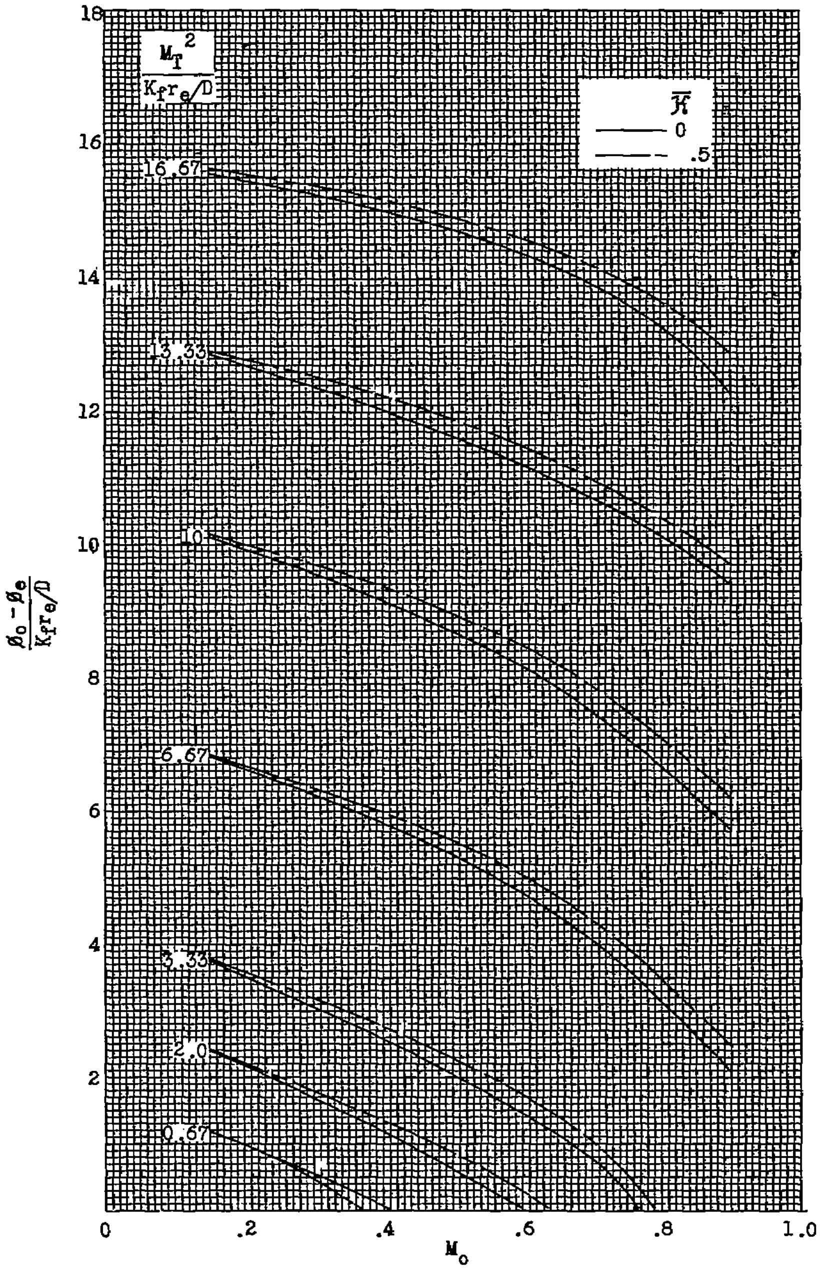
Figure 1.- Plot of Mach number function ϕ against Mach number. $\gamma = 1.40$; $\phi = \log_e \dfrac{M^2}{\left(1 + \dfrac{\gamma - 1}{2} M^2\right)^{(\gamma+1)/(\gamma-1)}}$.



(a) $\frac{T_a}{T_{t,o}} = 0.95.$

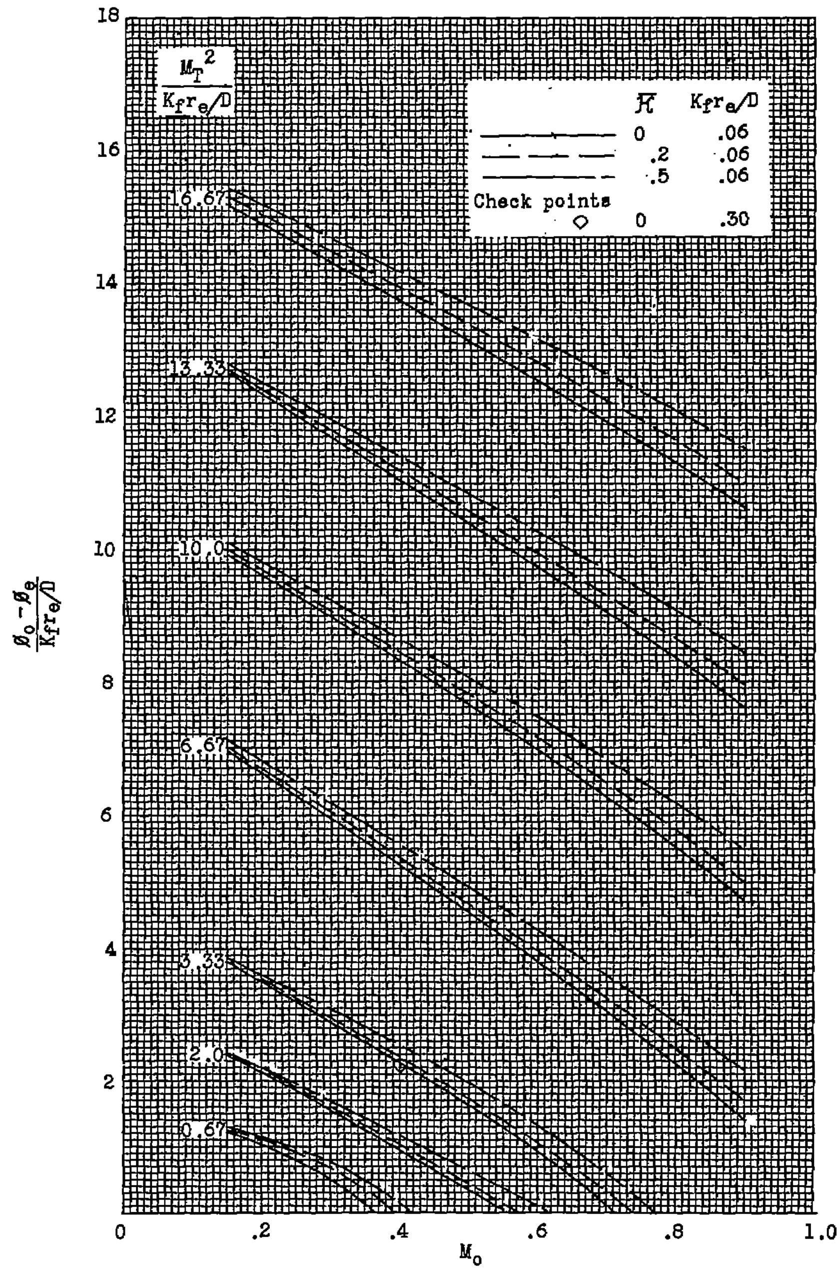
Figure 2.- Charts for estimating change in Mach number in constant-diameter duct as a function of duct Mach number at center of rotation.

E



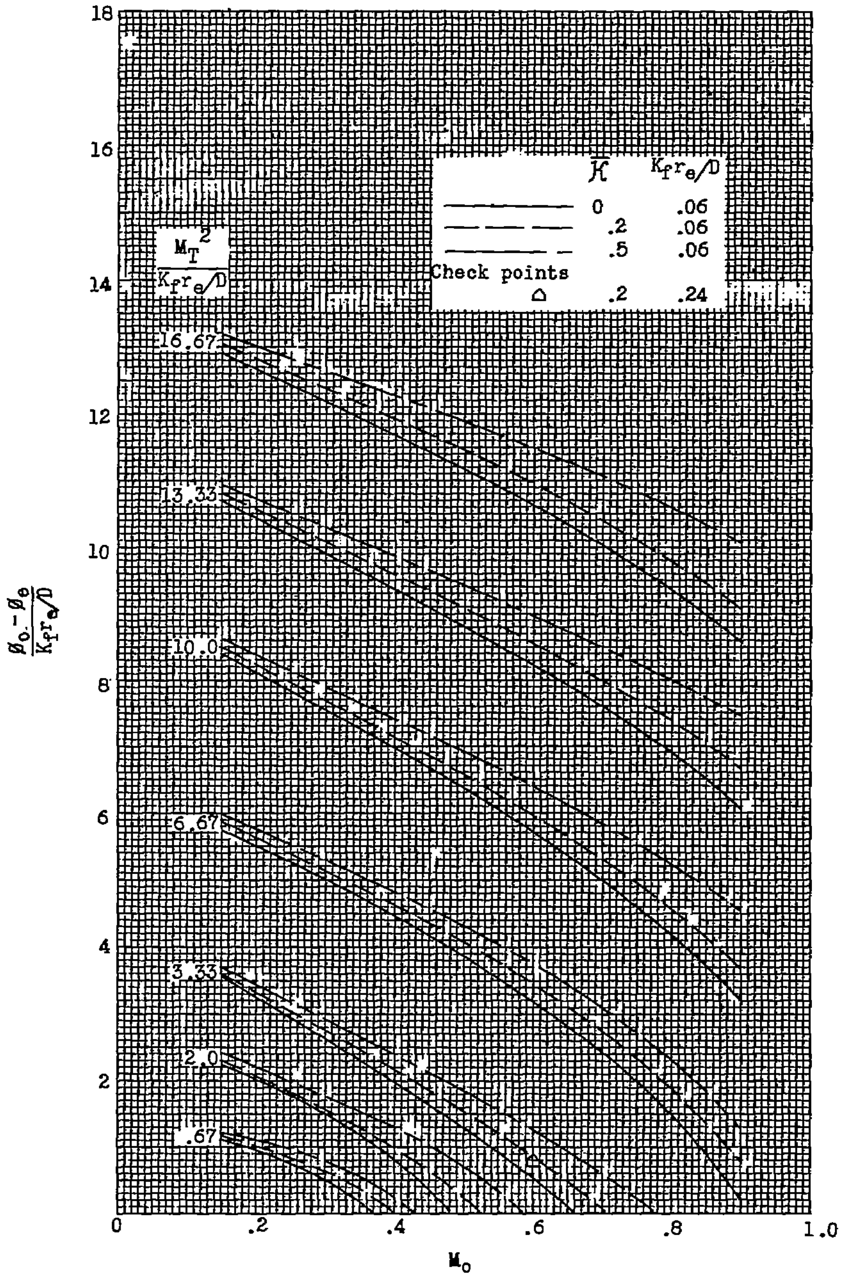
(b) $\frac{T_a}{T_{t,o}} = 0.85.$

Figure 2.- Continued.



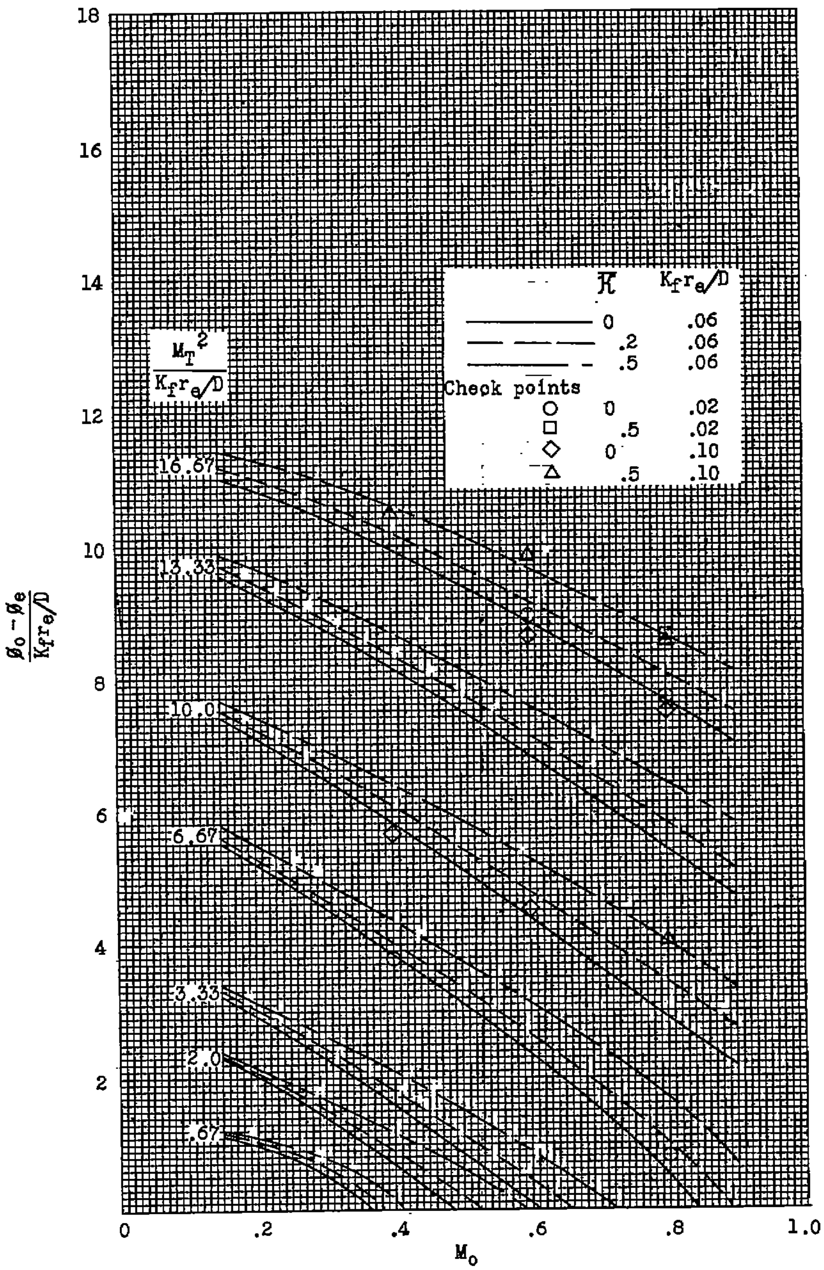
(c) $\frac{T_a}{T_{t,o}} = 0.75.$

Figure 2.- Continued.



(d) $\frac{T_a}{T_{t,o}} = 0.65.$

Figure 2.- Continued.



(e) $\frac{T_a}{T_{t,o}} = 0.55.$

Figure 2.- Concluded.

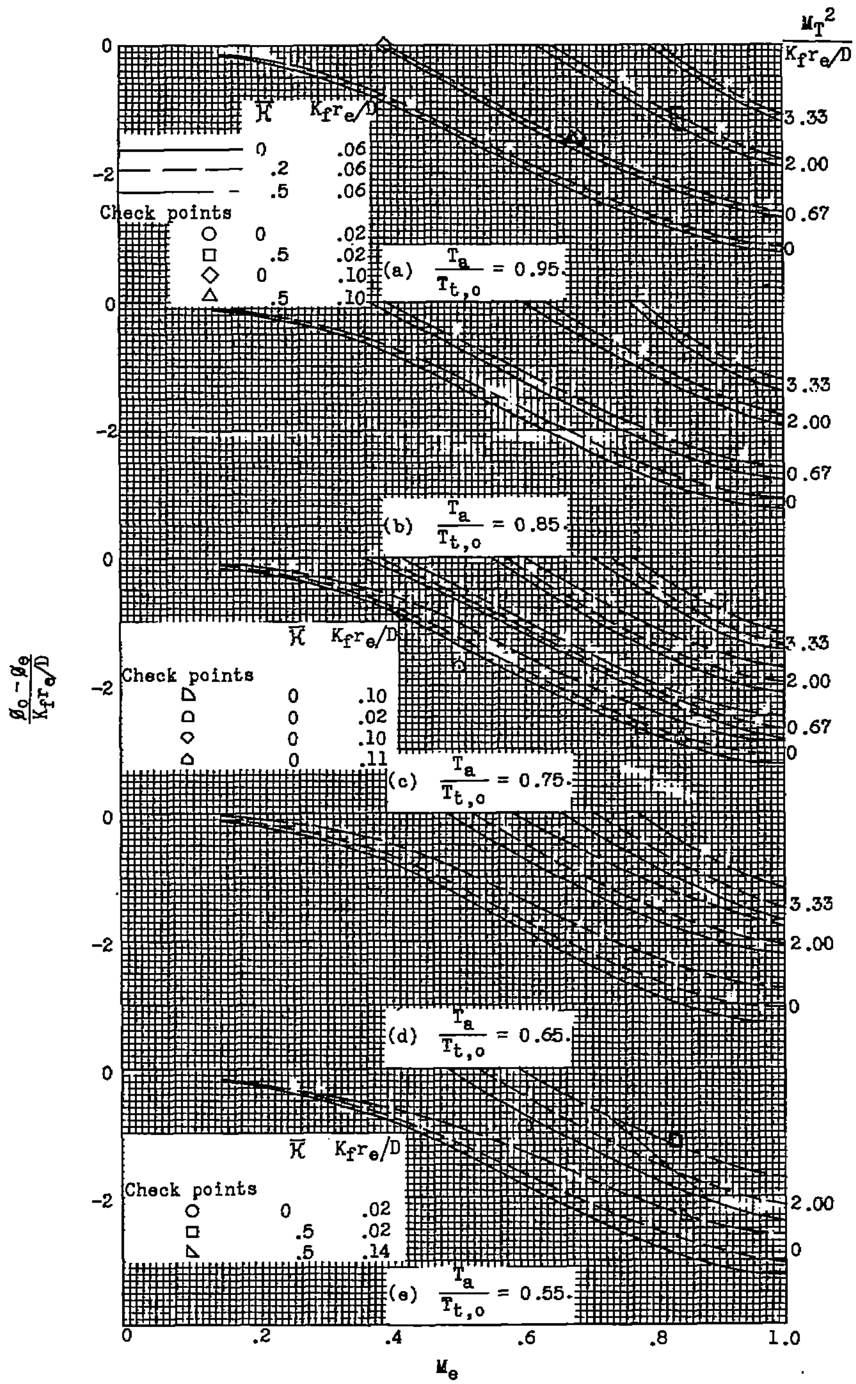


Figure 3.- Charts for estimating the change in Mach number in a constant-diameter duct as a function of duct-exit Mach number.